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Younger Dryas Glaciers and climate in the Mourne Mountains, Northern Ireland

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Abstract

Here, we present evidence to suggest that the Mourne Mountains, Northern Ireland, were last occupied by glaciers during the Younger Dryas Stadial. The margins of these glaciers are marked by moraines, chronologically constrained to the Younger Dryas by Schmidt Hammer exposure dating. Reconstructions indicate that these glaciers had equilibrium-line altitudes (ELAs) ranging from 356 ± 33 m (a.s.l.) to 570 ± 9 m (a.s.l.), with a mean of 475 ± 36 m (a.s.l.). ELAs rise from west to east, likely reflecting the contribution of windblown snow and ice to the accumulation of Younger Dryas glaciers in the western Mournes. Taking this into consideration, a mean 'climatic' ELA of 529 ± 4 m (a.s.l.) is calculated for the mountains as a whole. Assuming a mean annual sea level air temperature of -8°C , and an annual temperature range of 34°C , degree-day modelling suggests that during the Younger Dryas, accumulation at the 'climatic' ELA of glaciers in the Mournes was $846\text{--}990$ mm a^{-1} . This suggests increased aridity, relative to present, and is consistent with other parts of NW Europe, where reduced precipitation, alongside notable cooling is thought to reflect increased North Atlantic sea ice extent during the Younger Dryas.

Introduction

During the Younger Dryas Stadial (known in Ireland as the Nahanagan Stadial), equivalent to Greenland Stadial-1 (GS-1; c. 12.9–11.7 ka) (Lowe *et al.*, 2008), ice masses developed in many mountain ranges in NW Europe in response to rapid climatic cooling during the final stages of deglaciation from the Last Glacial Maximum (LGM) (Fairbanks, 1990; Renssen *et al.*, 2015). In many parts of Scotland, Wales, England, and Ireland, the extent of these glaciers, and the climate that allowed their formation, has been the focus of considerable study (e.g., Harrison *et al.*, 2010; Bendle and Glasser, 2012; Boston *et al.*, 2015). However, in Northern Ireland, though there is palaeoenvironmental evidence for cooling (e.g., Watson *et al.*, 2010; Walker *et al.*, 2012), climatic conditions and the extent of glaciers during the Younger Dryas remain

poorly understood (see Wilson 2004a,b; Rea and McCarron, 2008). One location where glaciers are presumed to have developed is in the Mourne Mountains (hereafter ‘the Mournes’) (Fig. 1), where geomorphological evidence suggests the former presence of small ice masses (Sutton, 1998; Wilson, 2004a). Analysing these former glaciers has important implications for understanding local and regional palaeoclimate, since the Mournes are located between the mountains of Scotland, NW England, North Wales, and western and eastern Ireland, where glacier-based climate reconstructions for the Younger Dryas have been generated (Ballantyne *et al.*, 2008; Golledge, 2010; Golledge *et al.*, 2010; Harrison *et al.*, 2010; Bendle and Glasser, 2012; Brown *et al.*, 2013). Given this significance, the purpose of this paper is to investigate the extent of glaciers in the Mournes during the Younger Dryas, and to reconstruct the climatic conditions under which they formed.

Study area and glacial history

The Mournes are located in NE Ireland, bordering the Irish Sea Basin (Fig. 1), they cover ~ 150 km², and reach a maximum altitude (Slieve Donard) of 850 m above sea level (a.s.l.). The mountains are primarily composed of a granite complex that was intruded into Silurian greywacke and slate country rock c. 56 Ma (Cooper and Johnston, 2004) (Fig. 1B), and have undergone multiple phases of glaciation during the Quaternary (see Dwerryhouse, 1923; Charlesworth, 1938; Stephens *et al.*, 1975; Gellatly, 1985; Sutton, 1998). At the LGM, known locally as the Glenavy Stadial (Bazley, 2004), the mountains were entirely submerged by the British Irish Ice Sheet (BIIS) which reached its maximum areal extent c. 27 ka (Clark *et al.*, 2012). Following the LGM, the deglaciation of the coast of NE Ireland likely occurred sometime before 18.2 ka (during the Cooley Point Interstadial) (McCabe *et al.*, 2007), when the BIIS retreated north and NW, away from the Mournes. This was followed by a period of ice sheet readvance, during the Clogher Head Stadial (c. 18.2–17.4 ka); retreat during the Linns Interstadial (c. 17.4 ka); before a final readvance during the Killard Point Stadial (c. 17.2–16.6 ka) (age estimates based on McCabe *et al.*, 2007, calibrated by Clark *et al.*, 2012). During these phases of readvance, the ice sheet moved south, but was deflected by the Mournes, and flowed east and west around their margins, with tongues of ice extending from North to South through the mountains. Following the Killard Point Stadial, the ice sheet retreated north and, despite later readvances, never again reached the Mournes (see McCabe and Clark, 1998; McCabe and Williams, 2012). Mountain glaciers are generally considered to have last occupied the Mournes during the Younger Drays Stadial (Sutton, 1998; Wilson, 2004a), as in other parts of Ireland (Colhoun and Synge, 1980; Anderson *et al.*, 1998; Harrison *et al.*, 2010) and Britain (Ballantyne, 2007a,b; Golledge, 2010; Bendle and Glasser, 2012), though no detailed analysis of the dimensions of these glaciers has been conducted (c.f. Sutton, 1998).

Methods

Geomorphological mapping

In order to establish the former extent of glaciers in the Mournes, the region’s glacial geomorphology was mapped from Bing aerial photographs and during field-based investigations. Though there are a number geomorphological indicators of former glaciation in the region, including erratic boulders, striations, glacially-smoothed bedrock surfaces, and roche moutonnée (Sutton, 1998; Wilson, 2004a), our focus was primarily on mapping moraines (though cirques were also mapped), on the grounds that they are the best geomorphological indicators of the dimensions of former mountain glaciers. Mapping was guided by Sutton (1998), and restricted to moraines within, or emanating from, the mountains, rather than considering the large and conspicuous moraines, which reflect former ice sheet extent, on adjacent lowlands (see Sutton, 1998; McCabe and Dunlop, 2006).

Establishing a glacial chronology

To establish a chronology for former glaciation in the Mournes, ideally a robust cosmogenic chronology would be established. However, to our knowledge, there are no published numerical ages to constrain the chronology of former glaciation in the mountains, and moraines are difficult to group morphostratigraphically (c.f. Lukas, 2006). In the absence of these data, Schmidt hammer exposure dating (SHED) was used in the present investigation. SHED is a long established technique for obtaining a relative chronology for surface exposure (Matthews and Shakesby, 1984), and has been widely applied to glacial environments (Goudie, 2006; Tomkins *et al.*, 2016). The principal of the method is that the Schmidt hammer is applied to a rock surface, and a rebound value (R) recorded. This R-value is considered a measure of rock strength—with stronger/harder surfaces returning higher R-values (Aydin and Basu, 2005). In formerly glaciated environments it is assumed that surfaces that have been glacier-free (i.e., exposed) for long periods will have experienced considerable weathering, and will therefore be ‘softer’, and return lower R-values, than more recently deglaciated areas. As a result, the procedure can be a simple and rapid way of establishing a relative chronology of deglaciation.

To obtain numerical age estimates using the technique requires independent dating control to generate R-value calibration curves (i.e., to convert R-values to numerical ages) (see Winkler, 2009; Matthews and Owen, 2010). Recently, Tomkins *et al.* (2016) produced a series of R-value calibration curves by sampling 76 surfaces in the UK, dated using Beryllium-10 (^{10}Be) Terrestrial Cosmogenic Nuclide Dating (TCND). Tomkins *et al.* (2016) produced individual curves for different lithologies, but found that granite surfaces alone demonstrate a statistically significant relationship between exposure age and R-values (see Fig. 2). In the present study, this calibration curve (Fig. 2) was used to establish a chronology of deglaciation in the Mournes. To allow direct comparison with their calibration curve, sampling procedures followed Tomkins *et al.* (2016). R-value measurements were taken using a ProceqTM ‘N’ type Schmidt Hammer. Sampling was restricted to horizontal (or near horizontal), dry surfaces on large boulders (> 1 m in length) or exposed bedrock surfaces (e.g., tors). In each case, the Schmidt hammer was held perpendicular to the surface, avoiding rough, irregular or lichen covered areas. To ensure that the sampled surfaces had been exposed to weathering continuously since deglaciation, samples were taken from sites away from cliff faces or valley walls, and in many cases sampled boulders were located on moraine crests (e.g., Fig. 3). At each location (e.g., on each moraine or summit) three surfaces and/or boulders were sampled, and, for each, 30 R-values were recorded (from numerous positions on each surface). In order to assess loss in Schmidt hammer condition over time, the same granite boulder was analysed at the beginning and end of sampling. This indicated a 2 point difference in R-values between the beginning (6 May 2016) and end of sampling (23 July 2016). By arranging the R-values chronologically, based on the date/time of collection, a correction was made assuming a linear deterioration in Schmidt hammer performance (following Tomkins *et al.*, 2016). To utilise Tomkins *et al.* (2016) R-value to numerical age curve for granite, our Schmidt Hammer required calibration against the University of Manchester calibration boulder (see Dortch *et al.*, 2016). This returned an average R-value of 48.70 ± 1.3 , compared to the calibration value of 48.08 ± 0.82 reported by (Tomkins *et al.*, 2016), and values were corrected to account for this difference.

Despite the lack of independent dating control, a number of characteristics likely make the Mournes a suitable location for applying the SHED approach outlined above. First, the mountains are dominated by granite lithology (see Fig. 1B), meaning that the calibration curve in Fig. 2 can be directly applied. Second, the mountain range is comparatively small (~ 150 km²) meaning that variations in climate (known to influence rock weathering rates) between sampled surfaces are likely to be minimal. Third, since the calibration curve (Fig. 2) is based

on dated surfaces from areas of the UK submerged beneath the BIIS during the LGM, and fully deglaciated by the onset of the Holocene, it is only really applicable to surfaces exposed during this period. Fortunately, the Mourne are considered to have experienced a similar glacial history to the sites sampled by Tomkins *et al.* (2016).

The granite SHED curve of Tomkins *et al.* (2016) is based on TCND, therefore SHED inherits some of the weaknesses of TCN methods. For example, rock surfaces can be exposed prior to final deposition, which would lead to a softer surface (lower R-value) and inherited TCNs. Conversely, post-depositional rock surfaces that have been exhumed or have spalled part of their surface off would lead to higher R-values and a reduced TCN concentration. Therefore, the calibrated SHED ages need to be analysed with appropriate statistics. Here, we followed the methods of Dortch *et al.* (2013) and Murari *et al.* (2014) and used the “ksdensity” kernel in MATLAB 2015a to produce probability density estimates (PDE). The PDEs were then modelled to separate out Gaussians to eliminate positive or negative skew. The highest probability Gaussian is selected with the peak and 1σ uncertainties reported, since all ages are younger than the LGM (c.f. Dortch *et al.*, 2013). Ages within 2σ that contribute to one of the selected Gaussians were compared using a two-tailed unequal-variance Student’s T-Test to determine if events are different.

Glacier reconstruction

The dimensions of Younger Dryas glaciers in the Mourne were reconstructed from mapped moraines. Based on the results of SHED, all cirques in the Mourne were presumed to have been occupied by glaciers during this period. Three-dimensional reconstructions of glaciers within, and/or emanating from, these cirques were generated using the GIS tool of Pellitero *et al.* (2016). In each case, a basal shear stress of 100 kPa was applied, using a step length of 10 m (for details see Pellitero *et al.*, 2016).

Equilibrium-line altitude estimates

A glacier’s equilibrium-line altitude (ELA) is defined as the altitude where net annual accumulation and ablation are equal, and is largely controlled by climate (Ohmura *et al.*, 1992). Estimating palaeo ELAs is therefore an established approach for obtaining palaeoclimatic information from glacier reconstructions (see Porter, 2001; Osmaston, 2005). In the present study, ELA was estimated using the GIS tool of Pellitero *et al.* (2015), applying the Area-Altitude Balance Ratio (AABR) method (considered the most robust method), with an AABR of 1.9 ± 0.81 (following Rea, 2009). As noted above, ELA is linked to climate, however in some instances, particularly in the case of small glaciers, ELA is also strongly influenced by non-climatic factors, such as the supply of snow and ice from indirect sources (i.e., from surrounding topography) (Kern and László, 2010). In order to assess the impact of this ‘redistributed’ snow and ice on the ELAs of reconstructed Younger Dryas glaciers in the Mourne, combined snow and avalanche contributing ratios were calculated (see Ballantyne, 2007a,b). This involved calculating the ratio of a glacier’s potential avalanche and snow contributing area (A_c) to its total surface area (A_g) (see Ballantyne, 2007a,b). A large A_c/A_g suggests a greater potential for redistributed snow and ice to make a notable contribution to glacier accumulation. In applying this approach to the Mourne, it was assumed that snow-bearing winds during the Younger Dryas were dominantly sourced from the west/SW (210–300°), as they are today (Betts, 1997).

Links to palaeoclimate

In order to estimate the climate necessary to sustain the reconstructed Younger Dryas glaciers in the Mourne, degree-day modelling (DDM) was utilised (see Laumann and Reeh, 1993; Braithwaite *et al.*, 2006). This approach, which has been widely adopted elsewhere (e.g.,

Hughes and Braithwaite, 2008; Barr and Clark, 2011; Bendle and Glasser, 2012), involves using an independent estimate of palaeotemperature to calculate annual melt (i.e., ablation) at the ELAs of reconstructed glaciers, based on an assumed melt rate. In the DDM approach, annual melt (M_a) at a glacier's ELA is calculated as the annual sum of daily melt values (M_d). Daily melt values are calculated by multiplying positive (i.e., $> 0^\circ\text{C}$) mean daily temperature (T_d) by a degree-day melt factor (DDF) (eq. 1).

$$M_d = T_d \times \text{DDF} \text{ (eq. 1)}$$

In this study a DDF of $4.1 \pm 1.5 \text{ mm } ^\circ\text{C}^{-1} \text{ day}^{-1}$ was used (Braithwaite 2008). By assuming that the annual distribution of temperatures is described by a sine curve (Hughes and Braithwaite, 2008), mean daily temperature (T_d) during the Younger Dryas was calculated from eq.2., using independent estimates of mean annual temperature (T_a) and annual temperature range (A_y) during this period (both from Isarin *et al.*, 1998).

$$T_d = A_y \sin\left(\frac{2\pi d}{\lambda} - \phi\right) + T_a \text{ (eq. 2)}$$

where A_y is the amplitude of annual temperature variability (1/2 of the annual temperature range), d the ordinal day, λ is the period (365 days), ϕ is the phase angle of the sine curve (here 1.93 radians based on the general assumption that temperature is maximal in July and minimal in January), and T_a is mean annual air temperature.

Since net annual accumulation and ablation at the ELA are considered equal, M_a calculated using this approach is considered an estimate of annual accumulation (considered a proxy for palaeoprecipitation) at the ELA of reconstructed glaciers.

Results

Geomorphology

Based on geomorphological mapping, it is apparent that distinct moraine sequences are found within, and adjacent to (within 500–1500 m), cirques in the Mourne (Fig. 1A). These upland moraines are distributed radially around the mountains, suggesting that they were deposited by mountain-centred ice masses, rather than by external ice flowing from the North. This assertion is supported by the lithology of debris within the moraines, which is predominantly comprised of locally-sourced Mourne granite (Wilson, 2004a). As such, these ridges are considered to have been deposited by former mountain- or cirque-style glaciers (Sutton, 1998; Wilson, 2004a). Lowland moraines occupy many of the region's trunk valleys (see Fig. 1A) and are widely presumed to have been deposited during the Killard Point Stadial, when larger glaciers occupied some valleys, and tongues of ice extended through the mountains from the BIIS located to the North (Sutton, 1998).

Chronology

To establish a chronology of deglaciation in the Mourne, a total of 53 separate locations (on mountain summits, cols, valleys, and cirques) were sampled for Schmidt hammer dating (see Fig. 1A). At each location, 30 R-values were recorded from 3 different surfaces (boulders or bedrock)—with measurements taken from numerous positions on each surface. Resulting SHED age estimates range from $6.5 \pm 0.8 \text{ ka}$ to $20.1 \pm 1.0 \text{ ka}$ (see supplementary information). Selected Gaussians from PDE models show a distinction between summit ($15.6 \pm 1.9 \text{ ka}$), col ($14.2 \pm 1.7 \text{ ka}$), valley ($10.5 \pm 1.4 \text{ ka}$) and cirque ($8.8 \pm 0.8 \text{ ka}$) locations (Fig. 4). The Gaussian models show a considerable amount of post-glacial exhumation or surface spallation affecting

summit and col age distributions (Fig. 4A–B). In contrast, cirque and valley age distributions are skewed by exposure prior to deposition leading to softer surfaces (Fig. 4C–D). Prior exposure is a common issue with TCND in the UK due to the lower erosivity of Younger Dryas ice. Cirque SHED age distribution is also considerably affected by exhumation or spalling of surfaces, which indicates considerable post-depositional reworking. P-values resulting from T-Tests on ages for each landform type within 2σ of the selected Gaussians are all < 0.01 . This indicates that, while there is some overlap of uncertainties, the events are statistically distinguishable and separate (See table 1). The data indicate that summits deglaciated following the LGM, closely followed by cols. Valleys last deglaciated during the late glacial (during phases of ice sheet readvance) and cirques last deglaciated following the Younger Dryas. The age estimates show some relationship with altitude ($R^2=0.27$, P-value < 0.01 ; Fig. 5). However, low altitude valley samples typically return older age estimates than higher altitude cirques (Fig. 5), thus the relationship likely reflects the region's glacial history, rather than an altitudinal control on the rate of post-glacial weathering (see Tomkins *et al.*, 2016).

Younger Dryas glaciers and their ELAs

On the basis of the geomorphological mapping and SHED chronology, 24 Younger Dryas glaciers were reconstructed in the Mourne (see Fig. 6). In places where multiple moraines potentially mark Younger Dryas ice margins, both minimum and maximum glacier reconstructions were generated (see Fig. 6). In total, the reconstructions indicate that during the Younger Dryas, the mountains were occupied by glaciers with a total surface area of 3.42–5.24 km² (see Table 2). These glaciers have ELAs ranging from 356 ± 33 m (a.s.l.) to 570 ± 9 m (a.s.l.), with a mean ELA of 475 ± 36 m (a.s.l.) (Table 2). Values for individual glaciers typically rise from west to east (Fig. 7A). This trend might reflect a precipitation gradient during the Younger Dryas, however when the impact of redistributed snow and ice is considered (Mitchell, 1996; Carrivick and Brewer, 2004), results indicate that ELA and snowblow and avalanche ratios (A_c/A_g) are related (Fig. 7B–C), and that glaciers in the western Mourne (labelled 1 and 2 in Figs. 7A & B) have comparatively large snowblow and avalanche ratios. This likely reflects their position on the lee (eastern) side of an extensive (~ 6 km²) upland plateau (Wilson, 2004a) (see Fig. 1A). This applies when both the minimum (Fig. 7B) and maximum (Fig. 7C) glacier reconstructions are considered. It is therefore possible that the plentiful supply of redistributed snow and ice explains the low ELAs of these glaciers, and that the West–East ELA gradient (Fig. 7A) is not climatically driven. Thus the reported mean ELA of glaciers in the Mourne during the Younger Dryas (i.e., 475 ± 36 m) (Table 2), is likely partly controlled by the availability of redistributed snow and ice (and cannot be directly linked to climate). In order to estimate a ‘climatic’ ELA, the regression lines in Fig. 7B–C can be extrapolated to simulate conditions for a hypothetical glacier receiving no accumulation from redistributed snow or ice (i.e., $A_c/A_g = 0$) (see Bendle and Glasser, 2012). Applying this technique in the Mourne yields a mean ‘climatic’ ELA of 529 ± 4 m (a.s.l.).

Degree-day model output

The DDM approach is used to predict annual accumulation in the Mourne during the Younger Dryas based on reconstructed glaciers and independent estimates of mean annual temperature and annual temperature range during this period. To simulate the coldest part of the Younger Dryas, a mean annual sea level air temperature of -8°C , and an annual temperature range of 34°C are assumed (Isarin *et al.*, 1998). With a DDF of 4.1 ± 1.5 mm $^\circ\text{C}^{-1}$ day⁻¹ (Braithwaite 2008), and an environmental lapse rate of 0.006 – $0.007^\circ\text{C m}^{-1}$ (Bendle and Glasser, 2012), this approach predicts annual accumulation of 844–2132 mm a⁻¹ at the mean ‘climatic’ ELA of Younger Dryas glaciers in the Mourne (Table 3).

Discussion

A deglacial chronology for the Mourne

Results from SHED in the Mourne (see supplementary information, and Fig. 4) are broadly consistent with the existing view of post-LGM glaciation in the region. Specifically, results indicate that summits were last deglaciaded during ice sheet retreat from the LGM, and that the higher cols were then exposed (Fig. 4). Valleys were last deglaciaded during the late glacial (likely during a phase of ice sheet readvance), and cirques were last glaciaded during the Younger Dryas. Despite the evidence to support this pattern, it is notable that the age estimates derived from the SHED approach are typically younger (more recent) than suggested by ‘established’ chronologies (Fig. 4). However, there are few chronologies available for comparison in Northern Ireland. Alternatively, the younger ages may indicate a limitation of the SHED approach applied here. Specifically, the local climate, or local granite that is slightly different to the granites in the calibration dataset, might mean that the Schmidt hammer calibration curve of Tomkins *et al.* (2016) is not directly applicable to the Mourne—something which might be addressed by establishing an independent cosmogenic chronology, from which a local Schmidt hammer calibration curve (equivalent to Fig. 2) could be constructed. Despite this, the SHED approach differentiates between different phases of glaciation in the Mourne (Fig. 4), and is considered a viable method for constraining the extent of the region’s glaciers during the Younger Dryas.

Younger Dryas climate in the Mourne

Meteorological data from Annalong (130 m a.s.l., ~54.11°N, 5.90°W) (labelled in Fig. 1A) reveals modern precipitation (AD 1931–1994) of 1227 mm a⁻¹ (Peterson and Vose, 1997). Adjusted to an altitude of 529 ± 4 m (a.s.l.), and assuming a rate of precipitation increase with altitude of 3.0 mm m⁻¹ (Brunsdon *et al.*, 2001), yields a modern precipitation estimate of 2424 ± 12 mm a⁻¹ at the ‘climatic’ ELA of Younger Dryas glaciers in the Mourne. By contrast, model data from the present study indicate that during the Younger Dryas, accumulation at this altitude was 844–2132 mm a⁻¹. This suggests a reduction in mean annual precipitation, relative to present. In fact, the temperature data used in the DDM (see Isarin *et al.*, 1998), with notably low winter temperatures and a greater annual temperature range, suggest that the Mourne likely experienced comparatively continental conditions during the Younger Dryas. Under such conditions, model outputs based on a DDF of 2.6 (the lowest value used in the present study) might be a better representation of ‘true’ Younger Dryas conditions (since higher DDFs are unrepresentative of glaciers occupying continental climates—see Braithwaite *et al.*, 2006; Hughes, 2009). When the model is run with a DDF of 2.6, results indicate mean accumulation of 846–990 mm a⁻¹ (Table 3), suggesting notable aridity during the Younger Dryas, relative to present. Unfortunately, though independent palaeoenvironmental proxies indicate cooling, landscape instability and the expansion of arctic shrub tundra in Ireland during the Younger Dryas (Watson *et al.*, 2010; Walker *et al.*, 2012), there is little information about precipitation during this period against which to validate these inferences. Despite this, the precipitation values reported here are comparable to those reconstructed for the Younger Dryas in parts of central and western Scotland (see Table 5 in Boston *et al.*, 2015), but generally lower than for parts of NW Wales (see Table 2 in Bende and Glasser, 2012).

Regional comparison

Modelling results from the present study suggest that Younger Dryas climate in the Mourne was continental, with particularly cold winters and reduced precipitation relative to present. Similar conditions have been proposed for other regions bordering the Irish Sea. For example, the Isle of Arran (Ballantyne, 2007a,b), Southern uplands (Cornish, 1981; Gordon, 1999), English Lake District (Sissons, 1980; Walker, 2004), and NW Wales (Bende and Glasser,

2012), are considered to have been notably drier than present during the Younger Dryas. Bendle and Glasser (2012) note that evidence for drier conditions is generally consistent with proxy archives (e.g. Isarin and Renssen, 1999) and ice core evidence (Alley, 2000) which suggest reduced annual snowfall across NW Europe during the Younger Dryas. The consensus view is that this aridity occurred as a result of low winter temperatures causing the formation of extensive sea ice (down to $\sim 50\text{--}52^\circ\text{N}$) in the North Atlantic (Renssen and Isarin, 1998; Renssen and Vandenberghe, 2003; Golledge *et al.*, 2010). Thus, conditions during this period may have been notably seasonal, with dry, arid winters (when sea ice was at its most extensive) and comparatively mild summers (Golledge, 2010; Bendle and Glasser, 2012). Under such conditions, moisture availability from the North Atlantic is considered to have been an important control on glaciation in NW Europe, with dominant westerly and southwesterly winds generating strong West–East precipitation (and associated ELA) gradients (Ballantyne, 1989; Sissons, 1979, 1980; Hughes, 2009; Golledge, 2010). For example, at Achill Island on the west coast of Ireland (~ 260 km west of the Mourne) moisture from the North Atlantic is considered to have sustained Younger Dryas glaciers with ELAs close to modern sea level (Bowen *et al.*, 2002; Ballantyne *et al.*, 2008), whereas in central and eastern Scotland ELAs were > 700 m (a.s.l.) (Boston *et al.*, 2015). Under such continental conditions, glaciers in the Mourne are likely to have been comparatively moisture-starved, and partly sustained because of a shortened ablation season, and the plentiful supply of redistributed snow and ice (Sutton, 1998). Golledge (2010) suggests that in western Scotland, extreme continental conditions during the most severe period of the Younger Dryas (with climate $6\text{--}8^\circ\text{C}$ cooler than present during the summer months, but as much as 30°C colder during the winter) were un conducive to glacier growth, and that perhaps glaciers were at their most extensive during the early stages of the Younger Dryas, when temperature depression and sea-ice induced aridity were less severe (Walker *et al.*, 2003; Walker, 2004; Bendle and Glasser, 2012). This may be true for the Mourne, and might explain why sequences of moraines are found within inferred maximum Younger Dryas glacier limits (Fig. 1A)—i.e., perhaps these ‘inner’ moraines reflect less extensive advances and/or periods of stabilisation during overall retreat from an early Younger Dryas ice extent maximum. Similar evidence, to suggest the development of comparatively extensive glaciers during the early Younger Dryas, has been found in other regions bordering the Irish Sea (see Bendle and Glasser, 2012).

Despite the evidence for increased aridity and continentality in NW Europe during the Younger Dryas, some regions appear to indicate precipitation totals comparable to, or even greater than, present. For example, in NW Scotland, there is some evidence of increased precipitation (by up to 26%) during the Younger Dryas (Ballantyne, 1989; Benn and Lukas, 2006; Lukas and Bradwell, 2010). However, in NW Scotland elevated precipitation is partly attributable to increased storminess, combined with the local presence of the Western Highlands ice field (see Golledge, 2008), which forced westerly and southwesterly air masses to rise and cool, meaning that adjacent areas (to the west) received heavy snowfall (Sissons, 1979, 1980; Ballantyne, 2007a,b). Such conditions are unlikely to have prevailed in the Mourne, and evidence from the present study appears to support the idea that Younger Dryas climate in Northern Ireland was colder, drier, and more continental than present. In fact, it is notable that insolation at these latitudes, and atmospheric CO_2 concentrations, were relatively high during the Younger Dryas (relative to earlier cold periods) (Imbrie *et al.*, 1984; Liu *et al.*, 2013), but freshwater inputs, ice bergs and sea-ice acted to cool North Atlantic climate by disrupting oceanic and atmospheric circulation (Isarin *et al.*, 1998; Bakke *et al.*, 2009; Golledge, 2010).

Conclusions

In this study, the extent of Younger Dryas glaciers in Mourne Mountains, Northern Ireland, has been reconstructed, and used to infer regional palaeoclimate. The main study findings are summarised as follows:

1. Geomorphological mapping reveals upland moraine sequences, suggesting the former presence of cirque and valley glaciers.
2. Results of SHED appear to chronologically constrain these moraines to the Younger Dryas, and are broadly consistent with the 'established' view of post-LGM deglaciation from the Mourne—i.e., with summits and some cols last deglaciated following the LGM, valleys last deglaciated during the late glacial (during phases of ice sheet readvance) and cirques last deglaciated following the Younger Dryas.
3. On the assumption that the region's cirques were last occupied during the Younger Dryas, 24 glaciers, covering 3.42–5.24 km², are reconstructed for this period. These glaciers have ELAs ranging from 356 ± 33 m (a.s.l.) to 570 ± 9 m (a.s.l.), with a mean of 475 ± 36 m (a.s.l.). These ELA estimates rise from west to east, but this is considered to reflect the supply of redistributed snow and ice to glaciers occupying the western Mourne, rather than indicating a clear climatic gradient.
4. When the role of redistributed snow and ice is accounted for, a Younger Dryas 'climatic' ELA of 529 ± 4 m (a.s.l.) is calculated for the mountains.
5. Assuming mean annual sea level air temperature of -8°C and an annual temperature range of 34°C (Isarin *et al.*, 1998), degree-day modelling suggests that during the Younger Dryas, annual accumulation at the 'climatic' ELA of glaciers in the Mourne was 844–2132 mm a⁻¹. However, given evidence for increased continentality in the region, annual accumulation was likely in the 846–990 mm a⁻¹ range, suggesting notably increased aridity relative to present. As in other parts of NW Europe, this reduction in precipitation, alongside notable cooling (with cooling of 7.0°C in summer, and 28.2°C in winter) is thought to reflect extensive North Atlantic sea ice (suppressing evaporation) during the Younger Dryas.

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Table 1. The peak age, 1σ uncertainties and P-values from T-Test between landform types at 2σ . P-values represent the relationship between the landform type they are listed across from and the next youngest in the table.

Landform	Selected Gaussian age (Ka)	P-values between 2σ Gaussian ages
Summit	15.6 ± 1.9	$\ll 0.01$
Col	14.2 ± 1.7	$\ll 0.01$
Valley	10.5 ± 1.4	$\ll 0.01$
Cirque	8.8 ± 0.8	N/A

Table 2. Attributes (including ELA estimates) of reconstructed Younger Dryas glaciers in the Mournes.

Glacier number	Glacier/Cirque name	Lat ($^{\circ}\text{N}$)	Lon ($^{\circ}\text{W}$)	Area min/max (km^2)	Z_{\min} min/max (m.a.s.l.)	Z_{\max} min/max (m.a.s.l.)	ELA (AABR: 1.9 ± 0.81) (m.a.s.l.)
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1	Shanlieve	54.121	6.088	0.18/0.52	287/217	476/478	356 ± 33
2	Eagle Mountain (min/max)	54.136	6.089	0.05/0.10	348/320	503/507	403 ± 9
3	Slieve Muck	54.153	6.037	0.20/0.37	405/331	592/611	483 ± 30
4	Carn Mountain (min/max)	54.162	6.033	0.10/0.23	451/410	604/612	524 ± 14
5	Lough Shannagh	54.170	6.018	0.39	408	561	471 ± 8
6	OTT Mountain	54.176	6.024	0.07	440	551	507 ± 5
7	Slieve Meelbeg	54.187	6.006	0.07/0.11	485/449	617/618	546 ± 19
8	Pollaphuca	54.189	5.994	0.12/0.15	404/403	666/668	523 ± 25
9	Hare's Gap North	54.192	5.976	0.08	335	450	398 ± 6
10	Hare's Gap South	54.191	5.967	0.13/0.19	383/362	536/543	456 ± 10
11	Spinkwee Valley	54.194	5.954	0.21	331	536	430 ± 12
12	Pot of Legawherry	54.191	5.946	0.11/0.17	458/420	653/659	546 ± 14
13	Shan Slieve	54.193	5.941	0.03/0.06	515/476	624/626	563 ± 16
14	Pot of Pulgrave	54.192	5.934	0.05	503	664	570 ± 9
15	Glen River (min/max)	54.185	5.930	0.11/0.15	427/408	585/590	498 ± 14
16	Eagle Rock (min/max)	54.188	5.919	0.11/0.16	414/410	664/668	506 ± 15
17	Thomas' Mountain	54.189	5.910	0.14	433	597	524 ± 9
18	Crossone (min/max)	54.182	5.905	0.25/0.37	362/339	578/591	465 ± 16
19	Chimney Rock Mountain (min/max)	54.167	5.914	0.14/0.20	437/380	668/669	539 ± 36
20	Rocky Mountain	54.162	5.926	0.29	386	530	468 ± 6
21	Castles of Commedagh	54.180	5.939	0.16	400	548	478 ± 7
22	Cove Lough (min/max)	54.172	5.956	0.12/0.37	446/436	600/629	530 ± 16
23	Slievelamagan	54.166	5.961	0.07/0.16	466/389	699/700	528 ± 63
24	Binnian Lough	54.150	5.977	0.24	453	649	544 ± 10
	Mean						475 ± 36

Table 3. Reconstructed annual accumulation in the Mourne during the Younger Dryas, based on a mean 'climatic' ELA estimate from reconstructed glaciers. Accumulation estimates are calculated using a degree-day model (see section 3.5).

Mean 'climatic' ELA (m.a.s.l.)	Lapse rate (°C m ⁻¹)	DDF (mm °C ⁻¹ day ⁻¹)	Accumulation at ELA (mm a ⁻¹)
529 ± 4	0.006	2.6	984 ± 6
529 ± 4	0.007	2.6	851 ± 7
529 ± 4	0.006	4.1	1551 ± 10
529 ± 4	0.007	4.1	1343 ± 11
529 ± 4	0.006	5.6	2119 ± 13
529 ± 4	0.007	5.6	1834 ± 24

Supplementary information

Supp 1. Schmidt hammer data from the Mourne Mountains. R-values, age estimates, and their uncertainties represent the mean and mean absolute deviation of 30 measurements per sample site. Numbered locations are shown in Fig. 1A.

Location number	Location classification	Sample	Latitude (°N)	Longitude (°W)	Sample type	Altitude (m.a.s.l.)	R-value	R-value Uncertainty	Age (ka)	Age uncertainty calibration curve (ka)	Total Uncertainty propagated quadratically (ka)
1	Cirque	1	54.1696	5.9124	Boulder	415	56.1	1.6	7.5		
		2	54.1693	5.9124	Boulder	423	54.2	1.7	8.4	1.60	1.61
		3	54.1686	5.9122	Boulder	449	56.7	1.9	7.2	1.60	1.61
2	Cirque	1	54.1217	6.0869	Boulder	303	54.6	1.7	8.2	1.60	1.62
		2	54.1215	6.0866	Boulder	297	56.5	1.6	7.2	1.60	1.61
		3	54.1216	6.0865	Boulder	296	55.5	1.7	7.7	1.60	1.61
3	Cirque	1	54.1518	5.9721	Boulder	454	57.3	2	6.9	1.60	1.61
		2	54.1506	5.9675	Boulder	451	52.8	2.5	9	1.60	1.65
		3	54.1497	5.9663	Boulder	447	55.8	2.6	7.6	1.60	1.63
4	Cirque	1	54.1362	6.0894	Boulder	359	53.6	1.4	8.7	1.60	1.61
		2	54.136	6.0887	Boulder	355	56	1.2	7.5	1.60	1.60
		3	54.1356	6.0882	Boulder	352	55.7	1.6	7.7	1.60	1.61
5	Cirque	1	54.1924	5.9488	Boulder	448	58	1.6	6.5	1.60	1.61
		2	54.1927	5.9482	Boulder	437	54.2	1	8.4	1.60	1.60
		3	54.1931	5.9464	Boulder	440	52.5	1.4	9.2	1.60	1.61
6	Cirque	1	54.1785	6.0302	Boulder	406	55.2	0.9	7.9	1.60	1.60
		2	54.1777	6.0288	Boulder	430	55.6	1.2	7.7	1.60	1.60
		3	54.1775	6.0254	Boulder	455	53.7	1	8.6	1.60	1.60
7	Cirque	1	54.1671	5.9556	Boulder	453	57	1.9	7	1.60	1.61
		2	54.1668	5.9543	Boulder	450	53.3	2.9	8.8	1.60	1.67
		3	54.1673	5.9506	Boulder	423	53.2	1.7	8.9	1.60	1.62
8	Cirque	1	54.1585	6.027	Boulder	353	51.4	2.2	9.7	1.60	1.65
		2	54.1585	6.0254	Boulder	362	54.9	1.2	8	1.60	1.61
		3	54.1426	6.0125	Boulder	370	56.9	0.9	7	1.60	1.60
9	Cirque	1	54.1925	5.9779	Boulder	351	54.2	1.6	8.4	1.60	1.62
		2	54.1928	5.9788	Boulder	343	55.3	1.2	7.8	1.60	1.61
		3	54.1938	5.9788	Boulder	337	53.6	1.7	8.7	1.60	1.62
10	Cirque	1	54.1378	6.0894	Boulder	360	55.7	1.5	7.7	1.60	1.61
		2	54.1371	6.0886	Boulder	337	53.1	1.7	8.9	1.60	1.62
		3	54.1371	6.0895	Boulder	351	54	1.5	8.5	1.60	1.61
11	Cirque	1	54.1874	5.9288	Boulder	428	52.6	1.8	9.2	1.60	1.63
		2	54.1867	5.9296	Boulder	440	55.9	1.1	7.5	1.60	1.60
		3	54.1867	5.9296	Boulder	439	53.1	1.2	8.9	1.60	1.61
12	Cirque	1	54.1912	6.0137	Boulder	395	52.8	2.2	9.1	1.60	1.64

13	Cirque	2	54.190 1	6.0121	Boulde r	425	52.2	1.9	9.4	1.60	1.63
		3	54.190 9	6.0128	Boulde r	405	56.2	2.2	7.4	1.60	1.62
		1	54.178 4	5.9397	Boulde r	423	53.1	1	8.9	1.60	1.60
		2	54.177 6	5.9415	Boulde r	391	53.3	1.4	8.8	1.60	1.61
		3	54.178 5	5.9418	Boulde r	401	54.7	1.5	8.1	1.60	1.61
14	Cirque	1	54.192 2	5.932	Boulde r	506	52.5	1.4	9.2	1.60	1.61
		2	54.192 4	5.932	Boulde r	512	53.6	1.8	8.7	1.60	1.62
		3	54.192 7	5.9322	Boulde r	522	54.9	1	8	1.60	1.60
15	Cirque	1	54.121 6	6.0808	Boulde r	252	53.4	1.3	8.7	1.60	1.61
		2	54.121 6	6.081	Boulde r	254	51.4	2.3	9.8	1.60	1.66
		3	54.121 3	6.0811	Boulde r	258	55.5	0.9	7.7	1.60	1.60
16	Col	1	54.154 3	6.1093	Boulde r	348	51.9	1.5	9.5	1.60	1.62
		2	54.155 3	6.1085	Boulde r	349	56.9	1.2	7.1	1.60	1.60
		3	54.155 5	6.1079	Boulde r	351	51.5	1.3	9.7	1.60	1.61
17	Valley	1	54.182 8	6.0372	Boulde r	382	54.7	2.1	8.1	1.60	1.63
		2	54.181 6	6.0377	Boulde r	410	53.2	3	8.9	1.60	1.67
		3	54.180 7	6.0343	Boulde r	385	51.7	1.3	9.6	1.60	1.61
18	Cirque	1	54.152 3	6.0359	Boulde r	422	50.5	1.1	10. 2	1.60	1.61
		2	54.152 2	6.036	Boulde r	426	52.2	1.4	9.4	1.60	1.62
		3	54.152 2	6.0356	Boulde r	418	55.9	1.3	7.6	1.60	1.61
19	Valley	1	54.147 5	6.0343	Boulde r	338	51.3	1.8	9.8	1.60	1.63
		2	54.147 1	6.0337	Boulde r	331	56.3	2	7.3	1.60	1.62
		3	54.147 2	6.0348	Boulde r	335	50.5	1.4	10. 2	1.60	1.62
20	Col	1	54.147 6	6.0941	Surfac e	404	50.9	1.3	10	1.60	1.62
		2	54.147 7	6.093	Surfac e	411	56.3	1.7	7.4	1.60	1.61
		3	54.147 6	6.0926	Surfac e	412	50.9	1.3	10	1.60	1.62
21	Cirque	1	54.191	5.9891	Boulde r	398	53.8	2.2	8.6	1.60	1.63
		2	54.191 7	5.9887	Boulde r	384	44.8	1.5	13	1.52	1.59
		3	54.191 7	5.9886	Boulde r	357	57.8	1.3	6.6	1.60	1.60
22	Summit	1	54.149 6	6.1123	Surfac e	438	51.9	1.3	9.5	1.60	1.61
		2	54.149 9	6.1122	Surfac e	437	53.2	1.2	8.9	1.60	1.61
		3	54.15	6.1122	Surfac e	436	51.2	1.6	9.8	1.60	1.63
23	Valley	1	54.16	6.1169	Boulde r	262	51.7	1.2	9.6	1.60	1.61
		2	54.159 8	6.1182	Boulde r	266	53.1	1.7	8.9	1.60	1.62
		3	54.160 2	6.1164	Boulde r	267	51.1	1.2	9.9	1.60	1.61
24	Valley	1	54.131 7	6.0786	Boulde r	212	52	1.3	9.5	1.60	1.61
		2	54.132 2	6.0776	Boulde r	201	52.4	1.7	9.3	1.60	1.62

25	Valley	3	54.132 2	6.0774	Boulde r	202	48.9	1.3	11	1.53	1.55
		1	54.144 7	6.0246	Boulde r	269	50.3	1.3	10. 3	1.60	1.62
		2	54.145 1	6.0241	Boulde r	266	52.7	1.8	9.1	1.60	1.63
26	Summit	3	54.145 7	6.0234	Boulde r	274	48.5	1.6	11. 2	1.57	1.61
		1	54.121 6	6.0935	Boulde r	486	51.6	1.8	9.6	1.60	1.63
		2	54.121 6	6.0937	Boulde r	488	50.8	1.6	10	1.60	1.63
27	Col	3	54.121 5	6.0937	Boulde r	489	49	1.8	10. 9	1.58	1.63
		1	54.173 7	6.0228	Surfac e	514	55.3	1.2	7.9	1.60	1.61
		2	54.174 2	6.0222	Boulde r	510	49.6	1.4	10. 6	1.59	1.61
28	Valley	3	54.174 1	6.022	Boulde r	511	46.4	3.4	12. 2	1.54	1.78
		1	54.194 7	5.9173	Boulde r	287	49.4	4.1	10. 7	1.58	1.82
		2	54.192 7	5.9217	Boulde r	308	48.3	2.1	11. 3	1.57	1.64
29	Valley	3	54.192	5.9216	Boulde r	315	52.8	1.3	9.1	1.60	1.61
		1	54.158 7	5.9731	Boulde r	352	52.3	1.7	9.3	1.60	1.62
		2	54.157 7	5.9648	Boulde r	341	49.7	2	10. 6	1.59	1.64
30	Valley	3	54.157 9	5.9618	Boulde r	337	47.5	2.1	11. 6	1.56	1.64
		1	54.156 6	5.9586	Boulde r	295	49.9	2	10. 5	1.59	1.65
		2	54.156 6	5.9585	Boulde r	294	49.3	1.9	10. 8	1.58	1.64
31	Valley	3	54.156 4	5.9585	Boulde r	293	47.5	2.2	11. 6	1.56	1.65
		1	54.171 8	5.8921	Boulde r	211	52.1	1.7	9.4	1.60	1.63
		2	54.172	5.8925	Boulde r	209	49.4	2	10. 7	1.58	1.64
32	Cirque	3	54.171 8	5.8927	Boulde r	216	45.1	1.5	12. 8	1.53	1.59
		1	54.167 9	6.0143	Boulde r	413	51.6	1.9	9.6	1.60	1.63
		2	54.166 2	6.0164	Boulde r	418	53.3	1.2	8.8	1.60	1.61
33	Summit	3	54.164 1	6.0196	Boulde r	413	39.9	1.4	15. 3	1.50	1.59
		1	54.189 5	6.0009	Boulde r	685	53.9	2.3	8.5	1.60	1.64
		2	54.190 3	6.001	Boulde r	675	49	2.8	10. 9	1.58	1.70
34	Col	3	54.191 3	6.0004	Boulde r	681	40.9	3	14. 9	1.50	1.86
		1	54.190 3	5.9731	Boulde r	441	43.6	3.1	13. 5	1.51	1.79
		2	54.190 3	5.9734	Boulde r	443	48.4	1.4	11. 2	1.57	1.60
35	Valley	3	54.190 3	5.9735	Boulde r	441	51.4	1.3	9.8	1.60	1.62
		1	54.195 4	6.0184	Boulde r	330	48.7	2.8	11. 1	1.57	1.70
		2	54.195 4	6.0184	Boulde r	332	47.5	2.1	11. 6	1.56	1.64
36	Cirque	3	54.195 4	6.0183	Boulde r	333	43.4	2.2	13. 6	1.51	1.66
		1	54.189 8	5.929	Boulde r	377	42.9	1.5	13. 9	1.51	1.59
		2	54.188 5	5.9282	Boulde r	403	41.9	2.1	14. 4	1.50	1.67
		3	54.188 2	5.9278	Boulde r	414	54.4	1.8	8.3	1.60	1.62

37	Summit	1	54.140 4	5.971	Surfac e	648	44.7	1.6	13	1.52	1.59
		2	54.140 4	5.9709	Surfac e	648	45.4	1.5	12. 7	1.53	1.59
		3	54.140 3	5.9709	Surfac e	649	49.1	2.1	10. 9	1.58	1.65
38	Col	1	54.172 2	5.9258	Bouler	529	46.3	2.3	12. 2	1.54	1.66
		2	54.172 9	5.927	Bouler	544	47.5	1.7	11. 6	1.56	1.61
		3	54.172 6	5.9282	Bouler	538	44.9	1.2	12. 9	1.53	1.56
39	Valley	1	54.136	6.0321	Boulde r	225	42.7	2.1	14	1.51	1.66
		2	54.136	6.032	Boulde r	224	48.6	1.2	11. 1	1.57	1.59
		3	54.136 1	6.0331	Boulde r	211	42.5	1.1	14. 1	1.51	1.55
40	Summit	1	54.167 6	5.919	Surfac e	604	41.9	1.5	14. 4	1.50	1.59
		2	54.167 2	5.919	Surfac e	614	47.1	2	11. 8	1.55	1.63
		3	54.167 4	5.9196	Surfac e	610	41.8	1.9	14. 4	1.50	1.64
41	Col	1	54.186 1	5.9962	Boulde r	522	44.8	1.6	12. 9	1.52	1.59
		2	54.185 9	5.996	Boulde r	517	43.7	2.2	13. 5	1.52	1.66
		3	54.185 9	5.9962	Boulde r	521	42	1.7	14. 3	1.51	1.61
42	Summit	1	54.184 8	5.99	Surfac e	731	43.1	1.5	13. 8	1.51	1.59
		2	54.184 8	5.9898	Surfac e	730	45	1.9	12. 9	1.53	1.62
		3	54.183 9	5.989	Surfac e	728	41.1	1.4	14. 8	1.50	1.58
43	Valley	1	54.139 8	5.94	Boulde r	182	39.3	0.9	15. 6	1.50	1.54
		2	54.141	5.9439	Boulde r	204	50.7	2.4	10. 1	1.60	1.67
		3	54.141 4	5.9468	Boulde r	219	36.7	1.5	16. 9	1.50	1.65
44	Summit	1	54.153 4	5.9812	Surfac e	654	41.5	1.2	14. 6	1.50	1.56
		2	54.153 7	5.9802	Surfac e	675	45	2.5	12. 9	1.53	1.69
		3	54.153 6	5.9805	Surfac e	659	39.7	1.1	15. 5	1.50	1.56
45	Col	1	54.183 9	5.9337	Tor	576	42.6	1.7	14	1.51	1.61
		2	54.183 9	5.9337	Tor	576	41.1	1.4	14. 8	1.50	1.58
		3	54.183 9	5.9337	Tor	575	41.1	2	14. 8	1.50	1.67
46	Valley	1	54.202 7	5.9943	Surfac e	253	40.6	1.8	15	1.50	1.64
		2	54.202 8	5.9948	Surfac e	258	42.6	2.3	14	1.51	1.69
		3	54.202 8	5.9947	Surfac e	257	40	1.9	15. 3	1.50	1.67
47	Summit	1	54.136 3	6.1	Surfac e	592	36.4	1.1	17. 1	1.50	1.59
		2	54.136 5	6.1003	Surfac e	598	40.5	1.6	15	1.50	1.61
		3	54.136 5	6.1008	Surfac e	605	39.3	2.7	15. 6	1.50	1.84
48	Summit	1	54.175 6	5.9556	Surfac e	623	38.5	1.4	16	1.50	1.61
		2	54.175 7	5.9551	Surfac e	627	40.8	1.7	14. 9	1.50	1.62
		3	54.175 8	5.9552	Surfac e	623	36.5	1.2	17	1.50	1.60
49	Summit	1	54.158 8	6.0396	Boulde r	662	38	1.6	16. 3	1.50	1.65

50	Summit	2	54.158 9	6.0397	Boulde r	661	39.3	2.3	15. 7	1.50	1.76
		3	54.158 6	6.04	Boulde r	659	38.2	1.8	16. 2	1.50	1.68
		1	54.167 3	6.029	Surfac e	585	37.1	1.2	16. 7	1.50	1.60
		2	54.167 2	6.0289	Surfac e	587	39.9	1.9	15. 4	1.50	1.67
		3	54.167 7	6.03	Surfac e	548	38.2	1.4	16. 2	1.50	1.61
51	Summit	1	54.165 1	5.9662	Surfac e	670	42.2	1.8	14. 2	1.51	1.62
		2	54.164 5	5.966	Surfac e	661	37.4	1.8	16. 6	1.50	1.70
		3	54.164 1	5.9657	Surfac e	654	35.6	1.3	17. 5	1.51	1.64
52	Summit	1	54.181 2	5.9201	Boulde r	835	38.4	1.5	16. 1	1.50	1.63
		2	54.180 6	5.9212	Boulde r	846	30.9	1	19. 7	1.55	1.68
		3	54.180 6	5.92	Boulde r	844	41.8	1.8	14. 4	1.50	1.63
53	summit	1	54.141 7	5.98	Surfac e	746	30.3	2	20. 1	1.57	2.05
		2	54.142 7	5.98	Surfac e	747	41.4	2.3	14. 6	1.50	1.71
		3	54.144 6	5.9795	Surfac e	709	37.2	2.6	16. 7	1.50	1.90

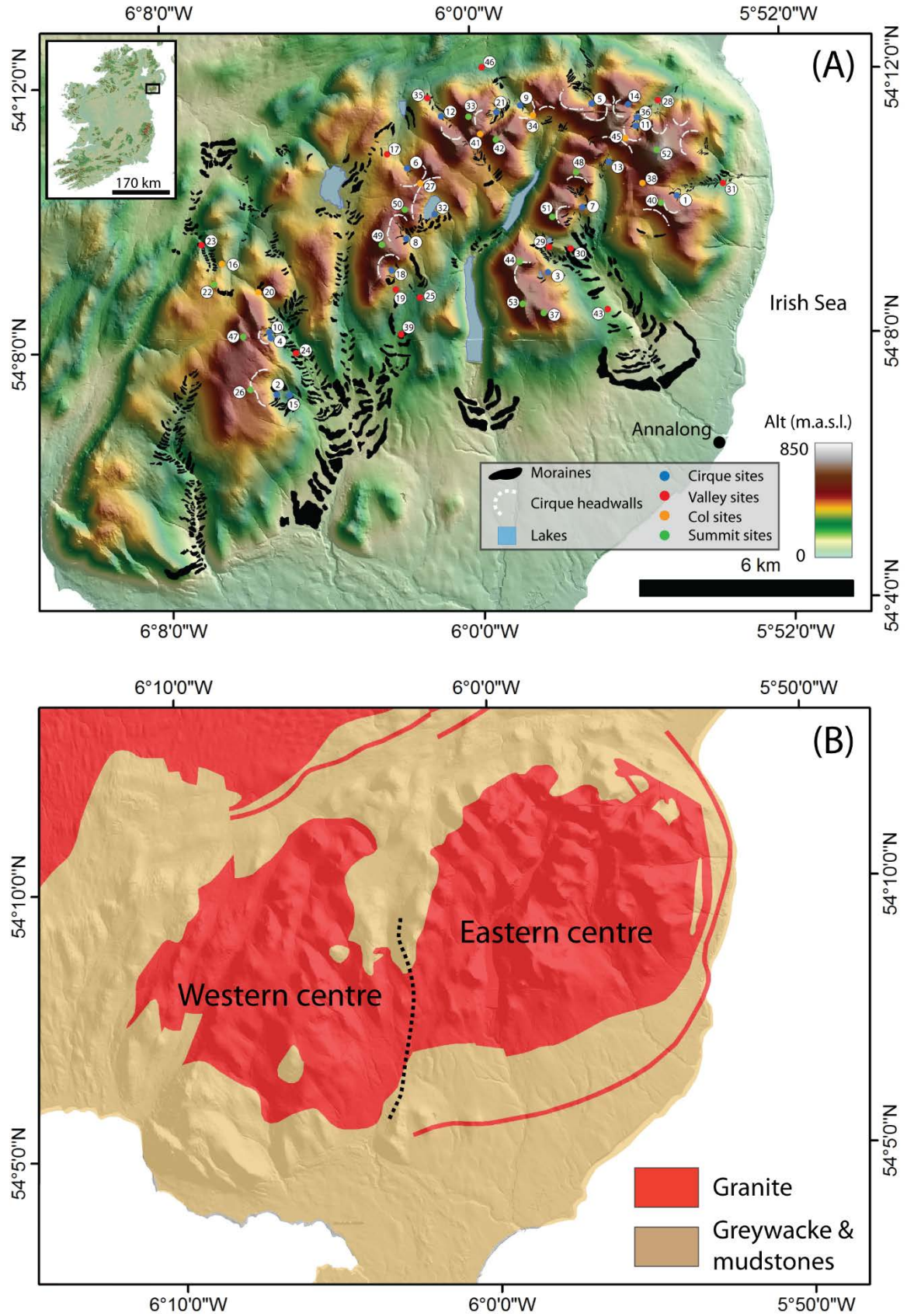


Figure 1. The Mourne Mountains, NE Ireland. (A) Geomorphological map. Sites mentioned in the legend refer to Schmidt hammer sampling locations, which are also numbered as in the Table S1. (B) Generalized geological map (GSI, 2016). The dashed line (in 'B') roughly marks the division between the Eastern Mournes (dominated by G1–G3 granites) and Western Mournes (dominated by G5 and G4 granites) (see Cooper and Johnston, 2004).

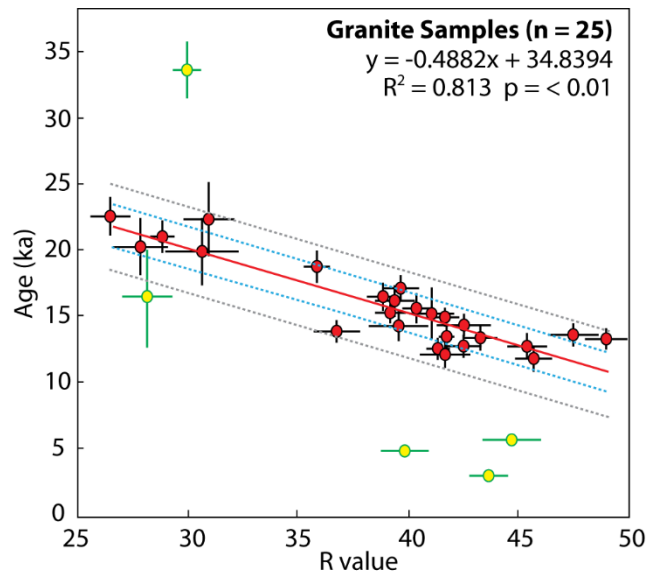


Figure 2. Schmidt hammer calibration curve for comsogenically dated granite boulders in the UK (curve developed by Tomkins et al., 2016). Here, R-values are plotted against ^{10}Be age. The regression line is shown in solid red. The blue and grey dashed lines denote one and two sigma boundaries, respectively. The data used to generate the regression line are shown as red dots with black error bars. Outliers, excluded from the calibration, are shown as yellow dots with green error.

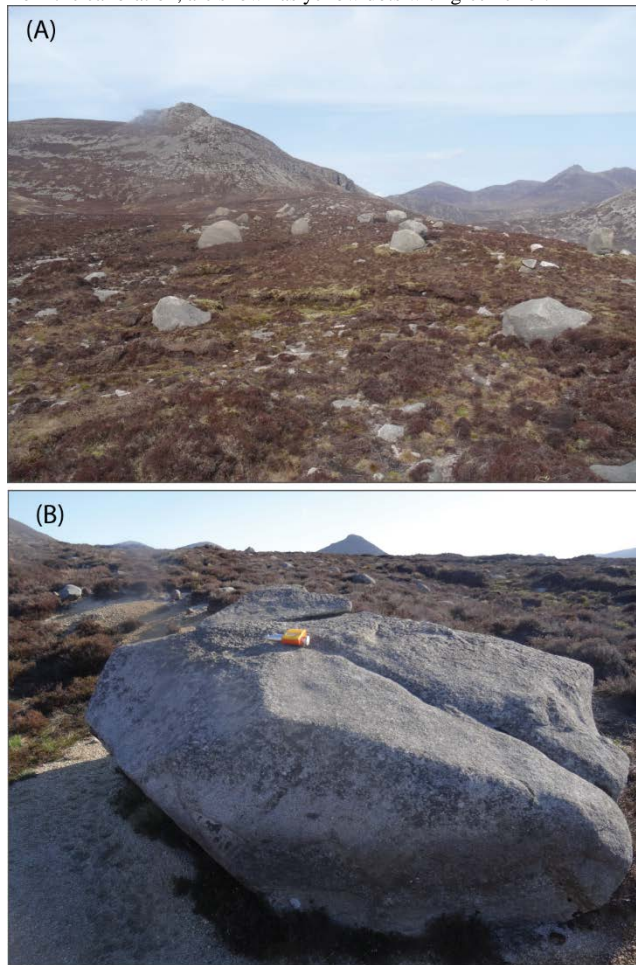


Figure 3. Examples of moraine crest boulder samples for Schmidt hammer exposure dating. (A) At Binnian Lough Corrie (54.151°N, 5.969°W). (B) At Carn Mountain Corrie (54.154°N, 6.026°W).

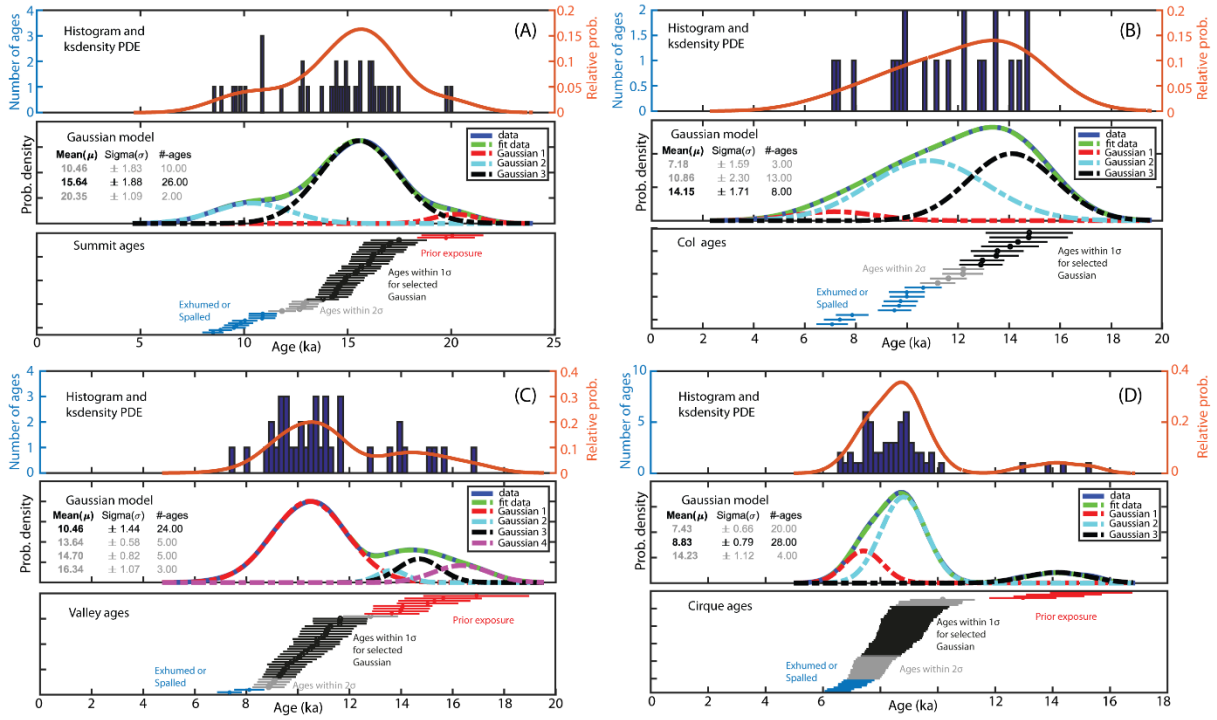


Figure 4. Probability density estimates and Gaussian models showing a distinction between ages [from: (A) summit (15.6 \pm 1.9 ka), (B) col (14.2 \pm 1.7 ka), (C) valley (10.5 \pm 1.4 ka) and (D) cirque (8.8 \pm 0.8 ka) locations].

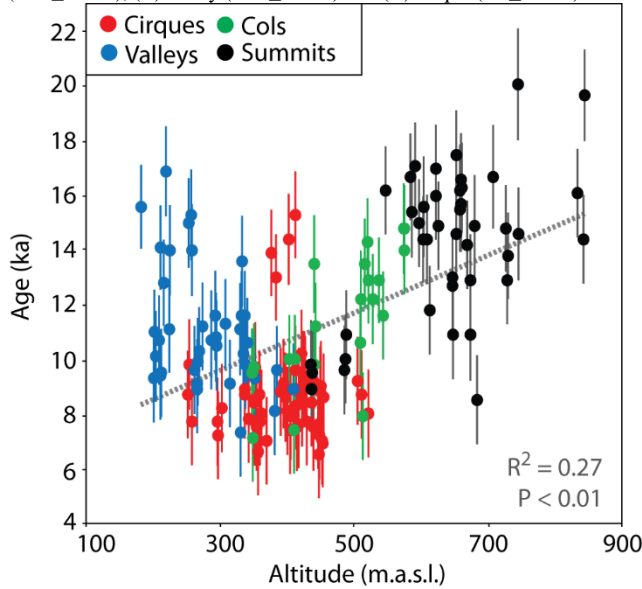


Figure 5. SHED age estimates plotted against altitude. For each site, the dot represents the mean value (based on 30 R-values per sample site). Error bars represent the quadratic propagation of the absolute mean deviation of R-values (30 hits) and one-sigma uncertainty from calibration against the granite regression curve of Tomkins et al. (2016). The dashed regression line reflects the trend for the entire dataset. Data are presented in Table S1.

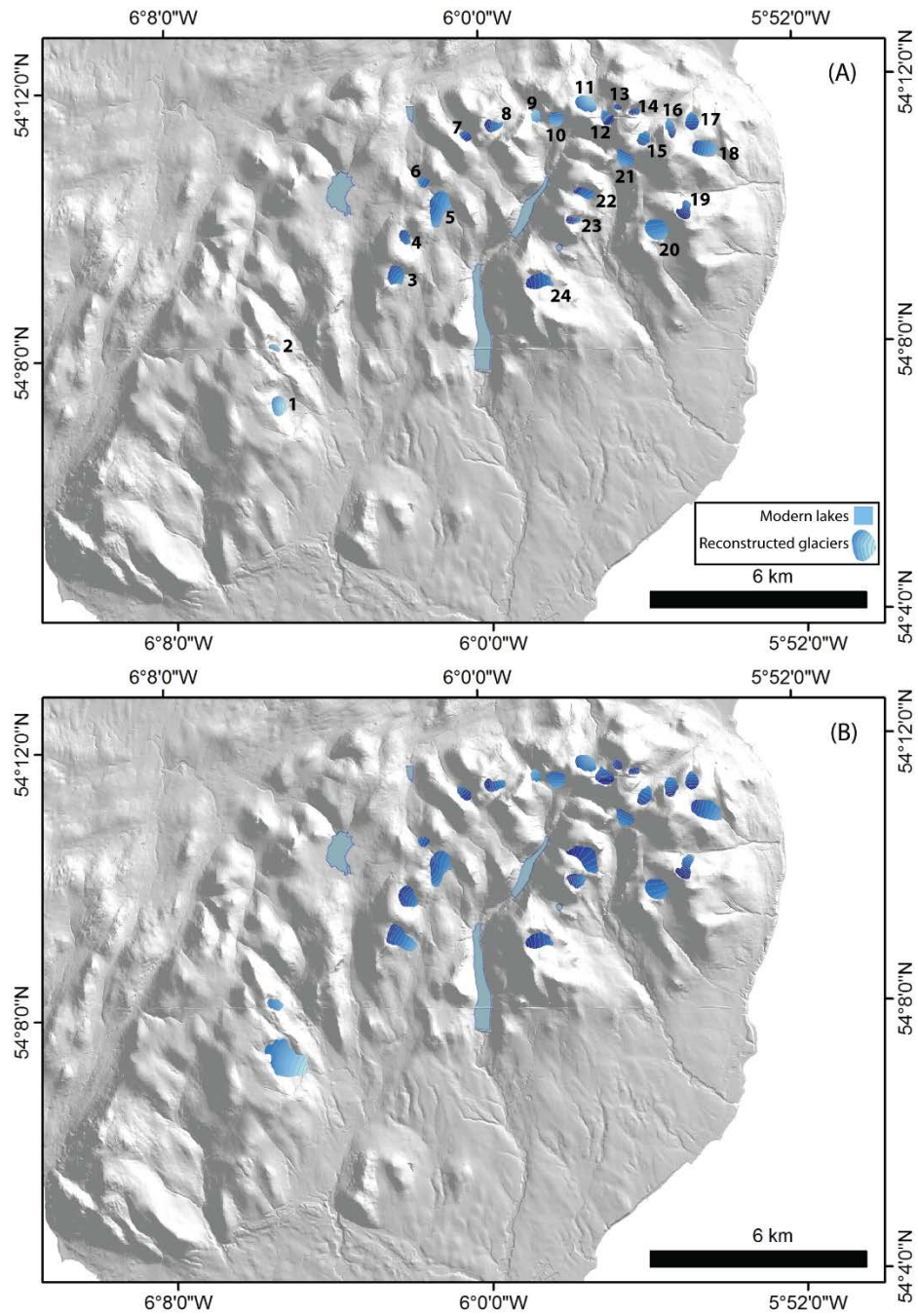


Figure 6. Minimum (A) and maximum (B) reconstructions of Younger Dryas glaciers in the Mourne. Glacier surfaces are contoured at 25-m intervals.

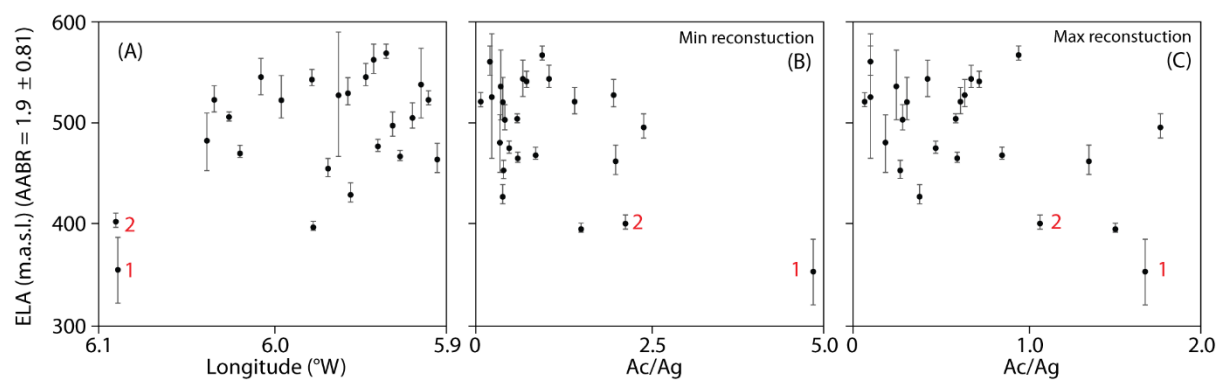


Figure 7. Equilibrium-line altitudes (ELAs) plotted against glacier (A) longitude, and (B,C) snowblow and avalanche ratios (Ac/Ag) for reconstructed Younger Dryas glaciers in the Mourne. Results from the minimum and maximum glacier reconstructions are shown in 'B' and 'C', respectively. Labels '1' and '2' refer to glaciers in the western Mourne (Fig. 6).